ULTRA-WIDEBAND TECHNOLOGY ENABLING LOW-POWER, HIGH-RATE CONNECTIVITY (INVITED PAPER)

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ABSTRACT

Ultra-wideband (UWB) technology has gone through some revolutionary changes this year, including the legalization of the technology in the US for imaging systems, vehicular radar systems, and communications and measurement systems. The allocation of 7.5 GHz worth of new, unlicensed spectrum that can be used for communications and measurement techniques, in particular, has sparked a renewed interest in both research and development of UWB technology in industry, universities, and government offices. However, a significant number of challenges remain for the technology to become ubiquitous. In this paper, a brief status of the UWB industry will be presented, including international regulatory and standards efforts that are currently underway. Then, some recent results on UWB channel modeling efforts for the indoor multipath channel are presented, which are critical when designing a high-rate UWB implementation. Finally, some specific challenges for UWB physical layer designs will also be presented, which could influence the long-term viability of the technology.

1. INTRODUCTION

According to the recent rules set forth by the FCC on February 14, 2002, ultra-wideband (UWB) systems are defined as systems that occupy more than 20% of a center frequency or more than 500 MHz bandwidth. For communications systems, the available spectrum is 7.5 GHz, from 3.1 GHz to 10.6 GHz, with slight differences in the spectral mask for indoor and handheld devices. So, from a high level perspective, this looks like a tremendous opportunity if one can figure out how to best, and in a cost effective manner, exploit this newly available bandwidth. This paper primary investigates the potential for UWB technology to be used for very high-throughput, short-range applications like high-speed cable replacement (USB cable replacement, for example), video distribution within the home, and fast image downloads from a camera to a wireless kiosk, for example. However, there are also a number of other uses of the technology that are currently being developed. These include: low-rate, low-power sensors; inventory tracking and cataloging devices; and radar and position location based applications, just to name a few. Many of these functions would also be beneficial to high-rate devices. Therefore, the ability for a single UWB physical layer solution to exploit high-rate, low-power, and accurate positioning capabilities of the technology could result in some interesting future capabilities. The following section will provide a current status of the industry in terms of regulatory and standards efforts world-wide. Then, the high-capacity promises of UWB technology are revisited for the applications of interest to demonstrate where the technology fits relative to other wireless, unlicensed technologies. Since an understanding of the propagation channel is critical for designing high-rate systems, recent results on channel modeling efforts are described in Section 4. Then, Section 5 describes several challenges that still exist for UWB system designs that could have a significant impact on the technologies future viability. Finally, conclusions are provided in Section 6.

2. CURRENT INDUSTRY STATUS

The regulatory process for making UWB systems commercially legal has taken a long road in the US. The FCC first initiated a Notice of Inquiry (NOI) in September of 1998, which solicited feedback from the industry regarding the possibility of allowing UWB emissions on an unlicensed basis following the same power restrictions for unintentional emitters described in the FCC Part 15 rules. Since this would result in UWB signals overlaying other wireless systems, it raised many concerns about the potential for interference to existing systems. In May of 2000, the FCC issued a Notice of Proposed Rule Making (NPRM), which solicited feedback from the industry on specific rule changes that could allow UWB emitters under the Part 15 rules. The interference concerns, especially related to safety critical systems like GPS, resulted in very large industry participation in the comment process to the FCC. More than 800 comments were filed during this period, including several very detailed interference studies (see FCC docket 98-153). Finally, on February 14, 2002, the FCC issued its final ruling allowing UWB systems to operate on an unlicensed basis under the Part 15 rules. According to statements by the FCC, these rules reflected a very conservative approach in order to protect existing wireless systems while allowing the technology to be further developed and proven. As a result, the opportunity exists to exploit this newly allocated spectrum, but many people in the industry and government are watching carefully to ensure that the technology does not disrupt current services.

Although the US successfully completed an initial round of regulations for UWB emissions (the FCC is expected to issue a 'Further' NPRM near the end of 2002 to revisit the current rules), the technology is still not legal anywhere else in the world. Regulatory bodies outside the US are also beginning discussion and interference studies of their own to determine possible rules to allow the use of UWB technology in their geographic region. For example, the International Telecommunications Union (ITU) SE24 study group is currently investigating emissions requirements for possible UWB devices, which will significantly influence European regulations. European standards are being developed within ETSI TG31a with a liaison relationship with IEEE 802.15.SG3a. There also appears to be interest in Japan, Singapore, and other countries. Hopefully, these regulatory bodies will consider harmonization, to some extent, with the FCC rules in order to allow devices to work in many parts of the world.

With the anticipation of the legalization of UWB systems, the IEEE 802.15.3 task group spawned a new study group (IEEE 802.15.SG3a) to investigate the possibility of developing a new, high-rate standard for short-range, wireless personal area networks (WPANs). Many of the companies participating in this effort anticipate that UWB technology would be a strong contender. Several applications were cited for justifying a new standard that provided > 110 Mbps throughput (twice that of any current standard) while maintaining low power consumption comparable to Bluetooth™ today. These applications included wireless cable replacement (USB cable replacement, for example), video distribution within the home, fast image downloads from cameras, and wireless connectivity of consumer electronic devices. As multimedia applications begin to appear on computers, cell phones, and PDAs as well as tradition consumer electronic equipment, there appears to be an opportunity to converge to a single standard for wirelessly connecting many devices in seemingly disparate markets (including personal computer, consumer electronic, and mobile markets). Of course, throughput is only one consideration, while low power operation and low cost are also critical for the success of this standard due to the desired use of the technology in many handheld devices. It is expected that proposals for this standard will appear in early 2003, so stay tuned.

3. UWB CAPACITY PROMISES

One of the promises that UWB technology offers is the ability to achieve a very high theoretical capacity. This can be seen by considering Shannon's capacity equation [1]:

$$C = B\log_2(1 + P/(NB))$$

where C is the Shannon capacity in bits per second, B is the bandwidth of the signal , P is the average received power, and N is the noise power spectral density. Note that, the FCC rules currently limit the transmit power spectral density, so the average transmit power will be $P = P_{sd}B$, where P_{sd} is the power spectral density limit allowed by the FCC. So, as the bandwidth of the UWB system increases, this equation suggests that the capacity will increase linearly with bandwidth, showing the sensitivity of UWB system capacity as a function of bandwidth. However, this is not the whole story. What is more interesting is to compare the capacity of a UWB system that is power spectral density limited with other unlicensed bands that may have narrower bandwidths but are average transmit power limited according to the FCC Part 15 rules. Figure 1 compares the capacity of a UWB system with other popular, unlicensed narrowband systems also defined under the Part 15 rules. This figure was derived using the following assumptions: N=-108 dBm/MHz (-114 dBm/MHz + 6 dB noise figure) and the path loss model for all systems is free space out to 8 meters with a path loss exponent of 3.3 beyond 8 meters (taken from current draft of the IEEE 802.15.2 Recommended Practice for WPAN operating in unlicensed frequency bands). Also, the transmit power for the various bands are as follows:

- 16 dBm for the lower UNII band (5.15-5.25 GHz)
- 23 dBm for the middle UNII band (5.25-5.35 GHz)
- 29 dBm for the upper UNII band (5.725-5.825 GHz)
- 30 dBm (1 Watt) for the 2.4 GHz ISM band (2.4-2.483 GHz)
- -41.3 dBm/MHz for UWB signals (3.1-10.6 GHz)

This figure clearly shows that there is a cross-over distance where the theoretical capacity is greater for UWB systems below this distance (approximately 10 meters), while the theoretical capacity is greater for the other unlicensed bands above this distance. This result suggests that, from the viewpoint of a high-throughput, short-range (less than 10 meters) design requirement, there is more potential for optimizing a UWB system under the current Part 15 rules than trying to optimize a system for the current unlicensed bands in the 2.4 and 5 GHz part of the spectrum. Conversely, this figure shows that optimizing the use of the other unlicensed bands may be preferable for longer range applications like WLANs. Figure 2 shows the throughput of a UWB system compared to an 802.11a system based upon practical link budget assumptions (6 dB noise figure, 6 dB link margin, 3 GHz UWB bandwidth, IEEE 802.15.2 indoor path loss model, Part 15 power levels for the middle UNII band for the 802.11a system, etc.), and shows the same trends predicted by the channel capacity theorem. Finally, it should be noted that these capacity results are very simplistic, since only AWGN is considered. Capacity that includes multipath propagation would be necessary to quantify the true upper limit of the channel capacity for all the systems discussed here.

4. UWB CHANNEL MODELING

In order to implement an efficient UWB system for high-rate communications, it's critical to understand the characteristics of the propagation channel. Intel performed several channel measurements spanning the frequency spectrum from 2-8 GHz (see [2] for more details). An example channel realization is shown in Figure 3, which points out two important characteristics of a very wideband, indoor channel.

First, as can be seen in the figures, the multipath spans several nano-seconds in time which results in inter-symbol interference (ISI) if UWB pulses are closely spaced in time. However, this interference can be mitigated in a number of ways through proper waveform design and signal processing and equalization algorithms. Second, the very wide bandwidth of a transmitted pulse results in the ability to individually resolve several multipath components. This is good and bad. It is good in the sense that the multipath arrivals will undergo less amplitude fluctuations (fading) since there will be fewer reflections that cause destructive/constructive interference within the resolution time of the received impulse. On the other hand, the average total received energy is distributed between a number of multipath arrivals. In order to take advantage of that energy, unique systems and receivers need to be designed with multipath energy capture in mind. For a traditional impulse based UWB waveform, this may consist of a rake receiver with multiple arms, one for each resolvable multipath component. However, as the bandwidth of the UWB waveform increases, the complexity of the RAKE receiver could become limiting in order to capture the same energy. As a result, careful bandwidth selection of the UWB waveform can help balance the receiver complexity for capturing multipath energy while still benefiting from the reduced fading of the short duration of the pulses.

In order to do proper system design, and understand and quantify the impact of multipath propagation, it's important to have a reliable channel model that captures the important characteristics of the channel. Towards this end, we have evaluated a number of popular indoor channel models to determine which model best fits the important characteristics that were measured and documented in [2]. The analysis and results of this channel modeling work have been submitted to the IEEE 802.15.3a channel modeling sub-committee [3], but are summarized here for completeness. Three indoor channel models were considered, the tap-delay line Rayleigh fading model [4], the Saleh-Valenzuela (S-V) model [5], and the Δ-K model described in [6]. Each channel model was parameterized in order to best fit the important channel characteristics, which included the mean excess delay, mean RMS delay, and mean number of significant paths defined as paths within 10 dB of the peak path power. Our results found that the S-V model was able to best fit the channel measurements and observed characteristics of the channel. In particular, the channel measurements showed a clustering of the multipath arrivals, which is also found in [7] and captured by the S-V model. In addition, the amplitude statistics of the measurements was found to best fit the log-normal distribution rather than the Rayleigh, which was part of the original S-V model. We have since compared the amplitude distribution to the Nakagami distribution and found that both the log-normal and Nakagami distributions fit the data equally well. So, the S-V model was modified slightly in order to take the log-normal fading distribution into account. The final proposed model is described next (see [3] for more details).

The proposed multipath model consists of the following, discrete time impulse response:

$$h(t) = \sum_{l=0}^{L} \sum_{k=0}^{K} \alpha_{k,l} \delta(t - T_l - \tau_{k,l})$$

where $\alpha_{k,l}$ is the multipath gain coefficient, T_l is the delay of the l^{th} cluster, and $\tau_{k,l}$ is the delay of the k^{th} multipath component relative to the l^{th} cluster arrival time (T_l). One consideration for the multipath model channel coefficients, $\alpha_{k,l}$, is whether they should be real or complex (with a magnitude and phase term). Some implications of this choice are the following:

1. If real coefficients are adopted, then the channel coefficients could be defined as $\alpha_{k,l} = p_{k,l} \beta_{k,l}$, where $p_{k,l}$ is equally likely to take on the values of +/-1, and $\beta_{k,l}$ is the lognormal fading term. The term $p_{k,l}$ is used to account for the random pulse inversion that can occur due to reflections, as observed in the measurements. Then, the real impulse response of the channel could be convolved with the real UWB transmitted waveform.
2. If complex coefficients are adopted, the complex, baseband equivalent channel model would need to be convolved with the complex, baseband representation of the transmitted waveform. For UWB pulsed systems, the meaning of phase is a bit ambiguous, since the transmitted waveforms are not necessarily carrier based. Since phase is directly related to delay for a given center frequency, it might be easier to account for phase for a specific waveform by

converting it into a delay given a center frequency of the channel and/or waveform. Since we have not characterized the distribution of the phase term, we can only suggest that a uniformly distributed phase in $[0,2\pi]$ could be a good model, based upon previous indoor channel models. In this case, the channel coefficients can be modeled as $\alpha_{k,l} = \beta_{k,l} e^{-j\phi_{k,l}}$, where $\phi_{k,l}$ is the random phase term uniformly distributed in $[0,2\pi]$, and $\beta_{k,l}$ is the lognormal fading term.

3. Due to the simplicity of the real channel coefficients, and to avoid the ambiguity of phase for an UWB waveform, we suggested adopting $\alpha_{k,l} = p_{k,l}\beta_{k,l}$, where $p_{k,l}$ is equally likely to take on the values of +/-1, and $\beta_{k,l}$ is the lognormal fading term.

Finally, the proposed model uses the following definitions (similar to [5]):

T_l = the arrival time of the first path of the l-th cluster;

$\tau_{k,l}$ = the delay of the k-the path within the l-th cluster relative to the first path arrival time, T_l;

Λ = cluster arrival rate;

λ = ray arrival rate, i.e., the arrival rate of paths within each cluster.

By definition, we have $\tau_{0l} = T_l$. The distribution of cluster arrival time and the ray arrival time are given by

$$p\left(T_l \left| T_{l-1}\right.\right) = \Lambda \exp\left[-\Lambda\left(T_l - T_{l-1}\right)\right], \quad l > 0$$

$$p\left(\tau_{k,l} \left| \tau_{(k-1),l}\right.\right) = \lambda \exp\left[-\lambda\left(\tau_{k,l} - \tau_{(k-1),l}\right)\right], \quad k > 0$$

The channel coefficients are then defined as follows:

$$\alpha_{k,l} = p_{k,l}\beta_{k,l}$$

$$20\log 10(\beta_{k,l}) \propto \text{Normal}(\mu_{k,l}, \sigma^2),$$

$$\{\text{or } \left|\beta_{k,l}\right| = 10^{n/20} \text{ where } n \propto \text{Normal}(\mu_{k,l}, \sigma^2) \quad \}$$

$$E\left[\beta_{k,l}^2\right] = \Omega_0 e^{-T_l/\Gamma} e^{-\tau_{k,l}/\gamma}$$

where T_l is the excess delay of cluster l and Ω_0 is the mean power of the first path of the first cluster, and $p_{k,l}$ is equiprobable +/-1. The μ_l term is given by

$$\mu_l = \frac{10\ln(\Omega_0) - 10T_l/\Gamma - 10\tau_{k,l}/\gamma}{\ln(10)} - \frac{\sigma^2 \ln(10)}{20}.$$

We used the proposed model to fit our measurements, and the following table provides the results of this fit for a couple of different channel scenarios (LOS refers to line-of-sight, and NLOS refers to non-LOS). Note that, when using the model, the total average received power of the multipath realizations is typically normalized to one in order to provide a fair comparison with other wideband and narrowband systems. This can be done either by normalizing each realization or by normalizing the total power, averaged over all realizations.

Channel Characteristics	***LOS***	***NLOS***	***LOS+ NLOS***
Mean excess delay (nsec) (τ_m)	4	17	14
RMS delay (nsec) (τ_{rms})	9	15	13
NP_{10dB}	7	35	33
Model Parameters			
Λ (1/nsec)	1/60	1/11	1/13
λ (1/nsec)	1/0.5	1/0.35	1/0.23
Γ	16	16	13
γ	1.6	8.5	6
σ (dB)	4.8	4.8	4.8

Table 1: Multipath channel characteristics and model parameters.

Although this study was intended to help evaluate physical layer proposals to the IEEE 802.15.SG3a committee, much more work remains on the characterization of UWB pulse propagation as a function of pulse bandwidth and operating environment. Many other contributions have also been submitted to the IEEE 802.15.3a channel modeling sub-committee work which describe measurements and models for a number of different environment. Although the goal of this work is primarily to provide a means for comparing various UWB physical layer designs, it is hoped that this work will yield a more general channel model that could be used for evaluating future UWB physical layer concepts.

5. CHALLENGES FOR HIGH-RATE UWB IMPLEMENTATIONS

High throughput UWB systems present a number of challenges as well as opportunities to be exploited, which are described in the following subsections.

5.1 Multipath mitigation and energy capture

Table 1 shows that, for a 167 psec multipath resolution, corresponding to a bandwidth of 6 GHz, there could be more than 30 significant paths that the receiver could capture. This represents a significant challenge for very wideband waveform and system design. In addition, excess delay spreads greater than 60-70 nsec were commonly observed, which suggests that some type of ISI mitigation might be required for very high rate implementations. Figure 4 (taken from [8]) shows the advantages of rake reception for a generic pulse based UWB implementation and a direct-sequence based UWB implementation (DS-UWB). A DS-UWB system refers to the concatenation of multiple UWB pulses to form a symbol. For example, a 100 Mbps DS-UWB system using BPSK modulation and a DS processing gain of 15 would have a chip rate of 1.5 GHz while the pulses could still occupy a bandwidth much greater than 1.5 GHz (in this case, the pulse waveform determines the occupied bandwidth, not the DS chip rate). This figure shows that energy capture using a rake receiver offers significant gains, and it shows that ISI and ICI (inter-chip interference) can also have a significant impact on performance in actual NLOS multipath realizations.

5.2 Narrowband interference impact on UWB receivers

The FCC spectral mask will make the coexistence between UWB and IEEE 802.11a wireless LANs an important consideration, since 802.11a devices will represent in-band interference for the UWB receiver front-end. In addition, the combination of WLANs and WPANs in a single device (like a laptop) could enable better connectivity options based upon the available resources, so solving the co-located design problem could yield low-cost, adaptable integrated products in the future.

5.3 UWB interference to other narrowband receivers

Product requirements and the future of UWB overlay systems will require UWB to peacefully coexist with other wireless systems, independent of the FCC rules. Therefore, UWB interference studies will continue to be important to help develop systems that offer better coexistence.

5.4 Low cost and low power consumption

Since many applications enabled by UWB technology are expected to be in handheld devices, low cost and low power consumption are critical. The low transmit power of UWB emissions allows for the possibility of greater integration of the baseband and RF circuits into CMOS. Since voltage levels available in CMOS get lower with time in order to provide faster speeds according to Moore's Law, low peak powers are needed to support a fully integrated RF front end in CMOS with no external power amplifier. Good UWB waveform design can keep the required voltage swings to within 100's of milli-volts, thus meeting the low peak voltage requirements for CMOS. Power consumption is not just a physical layer design challenge, but can also be solved with proper media access control (MAC) designs. The IEEE 802.15.3a MAC has been designed with low power consumption in mind, allowing for things like sleep periods between transmissions.

5.5 Scalable system architectures

Many of the application presentations made to the IEEE 802.15.3a study group included both high-rate applications like rapid transfer of images or video, as well as lower rate applications computer peripheral support (mice, keyboards) and stereo speakers. Therefore, a single radio standard that supports a range of data-rates and device capability is desirable, allowing for higher-cost devices that need the highest rates as well as lower cost devices that don't necessarily need very high rates.

5.6 Spectrum flexibility

The overlay ability of UWB technology offers the opportunity to 'fill-in' any unused portions of the frequency spectrum at any point in time, and can be viewed as 'opportunistic communications' where frequencies can be reused on a spatial basis. This could significantly help improve the overall efficiency of spectrum usage, which was a primary driving force behind the FCCs interest in this technology. A flexible system architecture that can take advantage of spectrum flexibility will not only help demonstrate the ability of UWB systems to peacefully coexist with other wireless systems, but also will allow systems to meet potentially different regulatory requirements that might be adopted elsewhere in the world. Although it is desired to have international harmonization of regulations world-wide, it may not be realistic in the short term.

5.7 High-rate Multi-hop Networking?

As a final application to consider, certainly a number of short-range capable devices could be networked in a multi-hop pattern to cover a much larger range than a stand-alone device. However, for a high-rate multi-hop network, a number of open issues still exist. As discussed earlier, UWB technology has its greatest capacity advantage at short ranges, while other narrowband technologies could yield a higher capacity at longer ranges. From a low-power consumption viewpoint, a short-range UWB device will likely have much lower power consumption than a longer-range technology, but from a cost viewpoint, the cost of many multi-hop radios has to be balanced with that of a single-hop radio. Therefore, for an application like in-home video distribution to a number of receivers that may be dispersed throughout the home, it's not clear whether a short-range multi-hop network would be more cost effective than a long-range single-hop radio. In fact, some combination of short- and long- range technologies could be a viable approach towards covering a larger overall region. Variations of these approaches are interesting research topics for enabling much higher-rate connectivity options for applications like in-home video distribution, where an installed network is not already present.

6. CONCLUSIONS

This paper provided an overview of some of the activities that are currently ongoing within the industry related to UWB regulations and standards. Although there appears to be significant benefits for using UWB technology for high-rate, short-range applications, there are still a number of challenges that merit further research. However, if these challenges are met and UWB implementations can be shown to peacefully coexist with other wireless systems, then there exists even greater potential for more efficiently utilizing the available spectrum and potentially opening up new spectrum in the future.

7. REFERENCES

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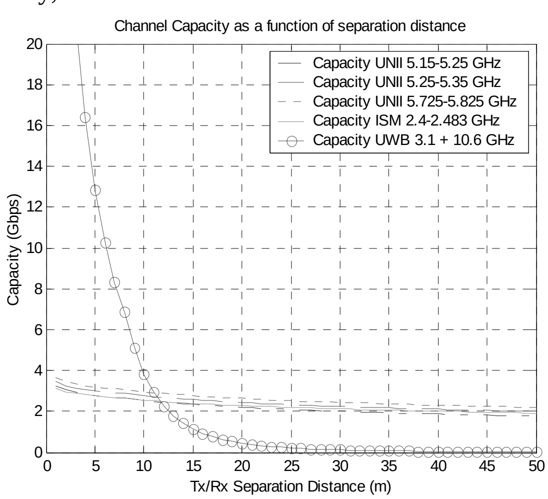

Figure 1: Theoretical capacity of unlicensed systems.

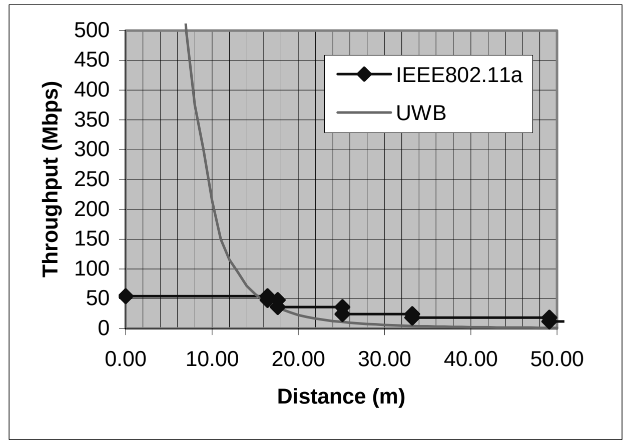

Figure 2: Practical throughput curves for UWB systems compared with IEEE 802.11a standard.

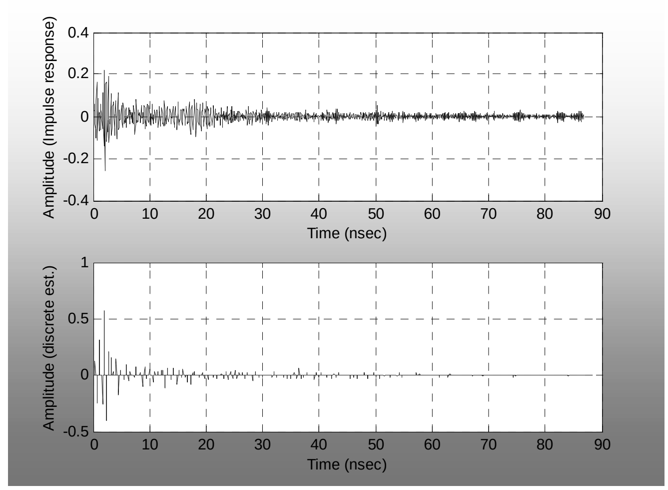

Figure 3. Example channel realization from an indoor channel.

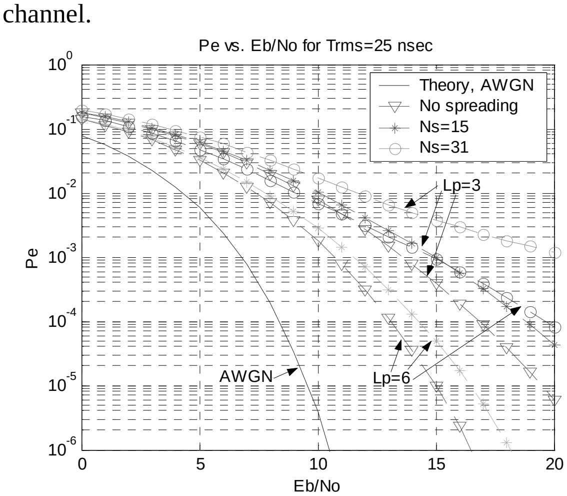

Figure 4: Performance of pulse-based and direct-sequence based UWB systems with *Lp*=3 and 6 RAKE arms, averaged over 50 NLOS channels and 100 Mbps.